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Abstract

This paper investigated the impact of rated voltage, under voltage and over voltage unbalance on induction motor operational performance using the International Electrotechnical Commission's (IEC) definition of voltage unbalance. This was used to determine the percentage of unbalance voltage that is tolerable for effective operational performance of an induction motor. MATLAB® Simulink was used to build a model for the performance analysis of a 2h.p induction motor and operated under balance and unbalance voltages at no load and loaded condition. The results obtained indicated gross efficiency when the motor is operated under various unbalanced conditions of rated voltage, under voltage and over voltage. The worst adverse effect of unbalance was most severe at under voltage conditions; drastic load reduction did not produce good motor performance even with a low Voltage Unbalance Factor (VUF). At over voltage unbalance however, motor indicated fair performance at VUF of 2-4% with a load reduction of 50%. At rated voltage unbalance with VUF of 2-4%, good performance was observed on load reduction of 50%. Above VUF of 4% for all types of unbalance, motor operation became grossly inefficient and load reduction did not improve operational performance of the induction motor.

Keywords: Induction motor, unbalance voltage, torque, speed, voltage unbalance factor (VUF).

1. Introduction

The widening power supply and demand gap is due to the increasing number of domestic, commercial and industrial loads. As power generation has not kept pace with the power demand, there has been an increasing stress towards energy management in the industrial sector as they are the major consumers. Adjustable-speed drives (ASDs) are finding increasing acceptance in industrial and commercial utilities for energy saving purposes (Kennedy, 2000). Power quality is a combination of voltage quality and current quality and is mainly concerned with the deviations of voltage and/or current from the ideal, and is termed as a power quality disturbance (Bollen, 2000). The frequent switching of most single phase loads such as computers, fluorescent lamps etc., also lead to a power quality problem; the harmful effects of which is quite damaging in the long run and has become one of the major concerns in recent years (Ezer et al., 2002). Power quality problem includes Unbalance Voltage, variation of

voltage, power frequency variation, waveform variation, transient etc. Unbalance and variations in supply voltage are the most common power quality problem. The main contributor to the voltages becoming unbalanced at the three-phase terminals is the unequal distribution and operation of single-phase loads across the power system network (Von Jouanne and Banerjee, 2001). This situation may also occur due to conditions within the utility premises as well. Though there may be fixed operating times within the utility premises, single-phase loads across the power system network continuously varies, usually with large hourly fluctuations, resulting in voltage variation and unbalance (Bhavaraju and Enjeti, 1996). Most importantly; the three-phase voltages tend to become asymmetrical in nature and application of asymmetrical voltages to three-phase induction motor driven system severely affects its working performance.

Three-phase induction motors are widely used in industrial, commercial and residential

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Keywords: Induction motor, unbalance voltage, torque, speed, voltage unbalance factor (VUF).

1. Introduction

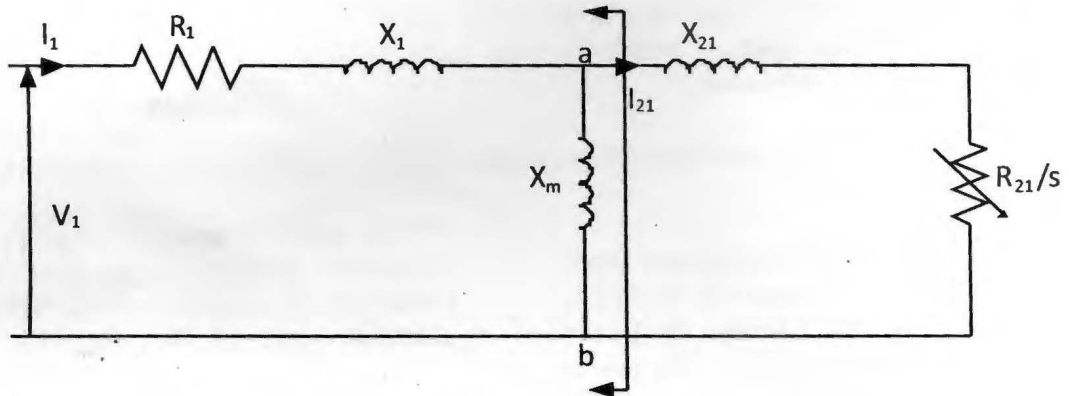
The widening power supply and demand gap is due to the increasing number of domestic, commercial and industrial loads. As power generation has not kept pace with the power demand, there has been an increasing stress towards energy management in the industrial sector as they are the major consumers. Adjustable speed drives (ASDs) are finding increasing acceptance in industrial and commercial utilities for energy saving purposes (Kennedy, 2000). Power quality is a combination of voltage quality and current quality and is mainly concerned with the deviations of voltage and/or current from the ideal, and is termed as a power quality disturbance (Bollen, 2000). The frequent switching of most single phase loads such as computers, fluorescent lamps etc., also lead to a power quality problem; the harmful effects of which is quite damaging in the long run and has become one of the major concerns in recent years (Ezer et al., 2002). Power quality problem includes Unbalance Voltage, variation of

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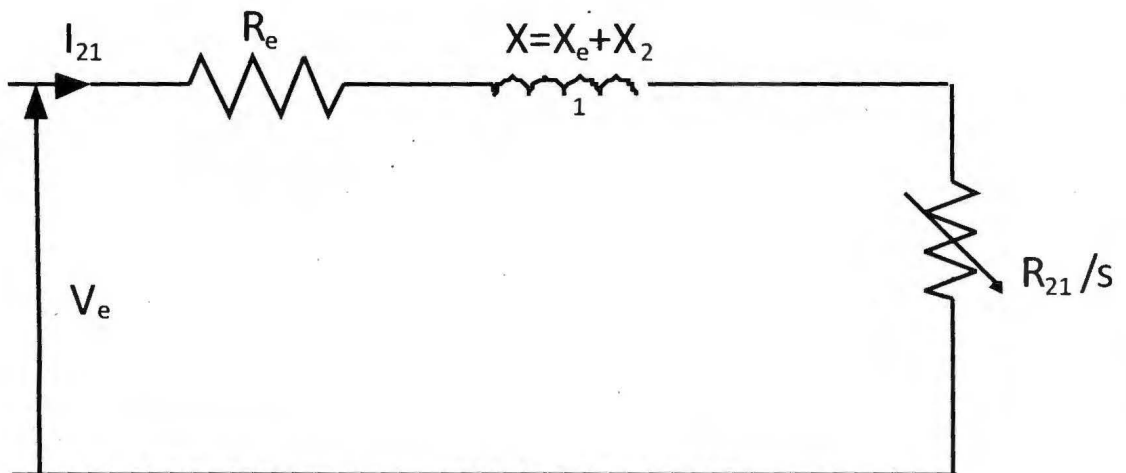
Three-phase induction motors are widely used in industrial, commercial and residential

electricity consumed in industry is used to drive electrical motors (Lawrie, 1987). The IEC Standard (IEC, 2008) and the European Commission's report (EC, 2000) show that induction motors in the power range from 0.75 kW to 4 kW represent a particularly attractive opportunity for electricity savings. The operation of three-phase induction motors under unbalanced voltages can cause serious ill effects such as overheating, drop of efficiency and reduction in output torque. In order to avoid the excessive heating in the windings the motor load has to be reduced so as to limit the temperature rise to the rated value. Therefore to maintain the operational life of the motor, the international standards (Von Jouanne and Banerjee, 2001; Kersting, 2001) recommend the derating of the motor. The continuous voltage variation and unbalance throughout the day does have a big impact on the working performance.

The greatest potential for energy savings is in electric motor applications and induction motors since they constitute over 64% of power usage. Industrial utilities make significant amount of investment in order to achieve energy efficiency, but many a times it has been found that performance variations in their process equipment are mainly due to external factors, in particular, the quality of the incoming supply (De Almeida et al, 2005). Hence, the knowledge of possible variation in performance due to the impact of voltage variation and unbalance is essential especially when it comes to identifying energy efficiency opportunities. The circuit of Figure 2.1(a) represents the usual equivalent circuit diagram of an induction motor while Figure 2.1(b) represents the Thevenin's equivalent circuit.



(a) Usual induction motor equivalent circuit



(b) Thevenin's equivalent circuit

Figure 2.1: Determination of Thevenin's equivalent circuit (Daniels, 1976)

Simulating Three-Phase Induction Motor Performance under Unbalance Voltage Condition.

When Figure 1(a) is viewed from points a and b, the single phase voltage, V_e is given by

$$V_e = V_1 \left(\frac{jX_m}{R_1 + j(X_1 + X_m)} \right) \quad (1)$$

While the single phase equivalent impedance,

$$Z_e = R_e + jX_e = \frac{(R_1 + jX_1)(jX_m)}{R_1 + j(X_1 + X_m)} \quad (2)$$

Where, Z_e is the single phase equivalent impedance, Ω

R_e is the single phase equivalent resistance, Ω

X_e is the single phase equivalent reactance, Ω

R_1 is the stator resistance, Ω

X_1 is the stator reactance, Ω

V_1 is the applied single phase voltage, V

I_1 is the stator current, A

S is the slip

R_{21} and X_{21} are the rotor resistance and reactance respectively referred to the stator.

It can be shown that the maximum torque, T_m is given by

$$T_m = \frac{m V_e^2}{2[R_e + \sqrt{j(R_e + X_e)}]} \quad (3)$$

Where, m is the number of phases.

The equivalent circuit parameters can be obtained from the no load and blocked rotor on the induction motor (Kothari and Nagrath, 2004).

The maximum torque, T_m varies as the square of the applied voltage. It is generally assumed that the applied voltage per phase is constant for the maximum torque to be guaranteed. However, as a result of unbalance loading condition prevalent in the Nigerian distribution network and prolong fault conditions, a wide variation in the applied voltage is a common experience. Most times the customers are connected to the distribution network before notifying PHCN. Thus, the utility company have little or no control over the loading of the phases by consumers. Rural electric power systems with long distribution lines and large urban power system with heavy single-phase demands are examples of reasons why single-phase loads are not uniformly spread among the three phases (Annette and Banerjee, 1975).

There are three fundamental definitions of voltage unbalance, namely;

(a) Phase Voltage Unbalance Rate (PVUR) defined by IEEE Standard 141 (Pillay and Manyage, 2001) the ratio of maximum voltage deviation from average phase voltage magnitude to the average phase voltage magnitude:

$$PVUR = \frac{\max [|V_a - V_{avg}|, |V_b - V_{avg}|, |V_c - V_{avg}|]}{V_{avg}} \quad (4)$$

Where, V_a, V_b, V_c are phase voltages

$$V_{avg} = \frac{V_a + V_b + V_c}{3} \quad (5)$$

(a) Line Voltage Unbalance Rate (LVUR) or Percent Voltage Unbalance (PVU) given by the National Electrical Manufacturers Association (NEMA, 2004) as follow:

$$PVU = 100 \times \frac{MVD}{V_{avg}} \quad (6)$$

where, MVD is the maximum voltage deviation from the average line voltage magnitude

V_{avg} is the average line voltage magnitude
 V_{ab}, V_{bc}, V_{ca} are line-to-line voltages.

(c) Voltage Unbalance Factor (VUF) that this definition has been given by International Electrotechnical Commission (IEC, 2008) as follow:

$$VUF = \left| \frac{V_-}{V_+} \right| \times 100 \quad (7)$$

A discrepancy of 13% is observed in the comparison of calculated VUF using both methods (IEEE, 2001). The IEC definition directly measures the impact of unbalance voltage on customers, hence it is used in this study.

Where, V_- and V_+ are the voltages of the negative- and positive-sequence components respectively; and are calculated by the method of symmetrical components developed by Dr. L. Fortescue in 1918. This definition provides a more accurate view of the voltage unbalance, because it calculates negative-sequence voltage that occurs as a result of the unbalance voltage.

These sequence systems can be given some physical interpretation. The direction of rotation of a three-phase induction motor when applied with a negative sequence set of voltages is opposite to what is obtained when the positive sequence voltages are applied. The negative sequence unbalance is the quantity of practical significance as it indicates the level of voltage that attempts to turn a three-phase induction motor in a direction opposite to that established by the positive sequence voltages. The negative sequence voltage unbalance (Ali, 2011) can also be expressed in a more user-friendly form as given by equation 8 which requires only the three line-line voltage readings.

Negative sequence balance is

$$\frac{V_2}{V_1} = \sqrt{\frac{1 - \sqrt{3} - 6\beta}{1 + \sqrt{3} - 6\beta}} \quad (8)$$

Where β is

$$\frac{V_{ab}^2 + V_{bc}^2 + V_{ca}^2}{(V_{ab}^2 + V_{bc}^2 + V_{ca}^2)^2} \quad (9)$$

This is also sometimes known as the Voltage Unbalance Factor (VUF) or the IEC definition in some literature.

The aim of this study is to use International Electrotechnical Commission's (IEC) definition of voltage unbalance to investigate the level of difference in the operating performance of induction motors working under balanced and unbalanced voltage. The objectives of this study are to:

- i. Determine the percentage of unbalance voltage that is tolerable for effective operational performance of an induction motor.
- ii. Determine the impact of rated voltage, under voltage and over voltage unbalance on induction motor operational performance.
- iii. Measure the voltages supplied to the Department's machine laboratory and simulate the performance of a three phase induction motor based on the measured voltage value.

2. Materials and Method

The technical data of the three phase induction motor investigated is presented in Table 2.1.

Parameter	Value
Rated Voltage (V)	415(L-L)
Power (kW)	1.5
Frequency (Hz)	50
Speed(rpm)	1500
Mutual Inductance	0.2037
Number of Poles	4
Parameter	Value
Stator Resistance	
Stator Inductance	0.005974Ω
Rotor Resistance	1.083Ω
Rotor Inductance	0.005974Ω

In order to evaluate the performance of the motor, it was first subjected to test operations under rated conditions with balanced voltage at no load. Thereafter, to evaluate the influence of unbalanced voltage on its performance, the motor was tested with three types of three-phase voltage unbalance under load presented in Table 2.2.

To study the under voltage unbalanced condition, the positive sequence voltage was fixed at 95% of the rated voltage and the simulation was performed for five different values of VUF between 2% and 10%. To study the rated-voltage unbalanced condition, the positive sequence voltage was fixed at the rated voltage and simulation conducted for five different grades of VUF from 2% to 10%. Finally, to study the over-voltage unbalanced condition, the positive sequence voltage was fixed at 105% of the rated voltage and simulation performed for five different values of VUF from 2% to 10% are presented in Table 2.2. Furthermore, simulation was performed using the values of voltages obtained on 19th of December, 2012 from the Department's Machine Laboratory mains supply and the results presented in Table 2.3.

Simulating Three-Phase Induction Motor Performance under Unbalance Voltage Condition.

In this study, MATLAB[®] Simulink was used for the analysis performance of the induction motor. The model comprises a standard IEC three-phase induction motor fed by programmable three-phase power sources. The output of the machine and other electrical variables were monitored on scopes. The induction motor is totally enclosed fan cooled

(TEFC), with a cast aluminium squirrel cage. The model represents the machine under balance and unbalanced conditions created in the Simulink workspace and their parameters defined. The Simulink model for the balanced and unbalanced conditions is presented in Figure 2.2.

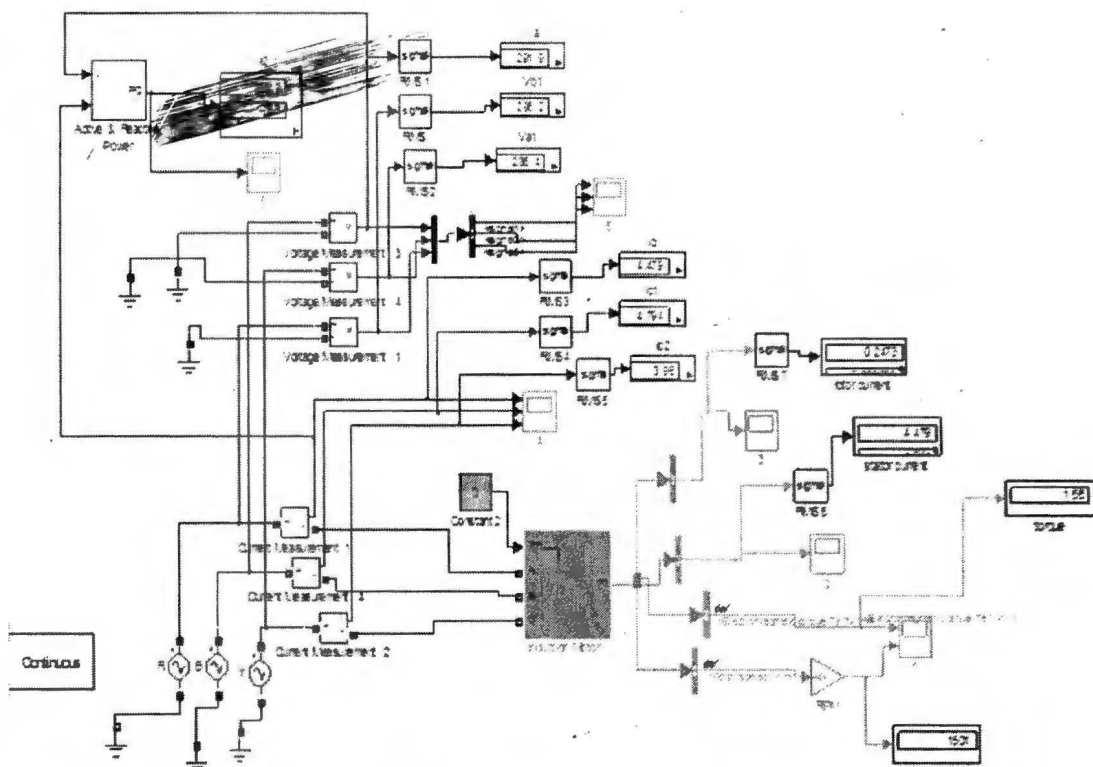


Figure 2.2: Simulink model for the balanced and unbalanced conditions

Table 2.2: Voltage unbalance

Type of Voltage unbalance	Per-Unit Voltage
Over-Voltage	1.05
Rated Voltage	1.00
Under-Voltage	0.95

Table 2.3: Measured Voltages in the Machine Laboratory of Electrical/Electronic Engineering Department

R-N(V)	Y-N(V)	B-N(V)
190	190	194

3. Result Analysis and Discussion

3.1 Results

The outcome and analysis of the simulation of the induction motor under balanced and unbalanced conditions are presented in time

3.1.1 Balanced Voltage

(a) Stator and Rotor Currents

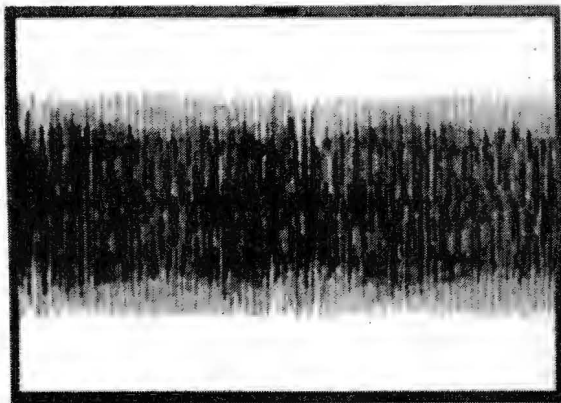


Figure 3.1: Stator currents on no load
Balanced voltage.

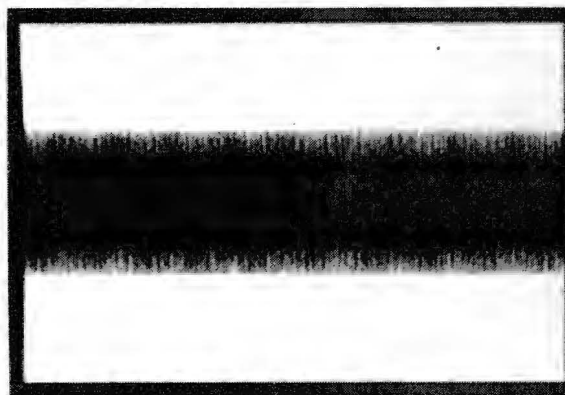


Figure 3.2: Stator currents on full load
Balanced voltage

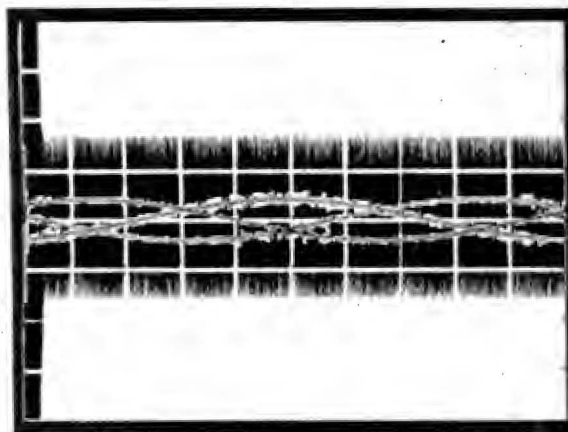


Figure 3.3: Rotor currents on no load
Balanced voltage

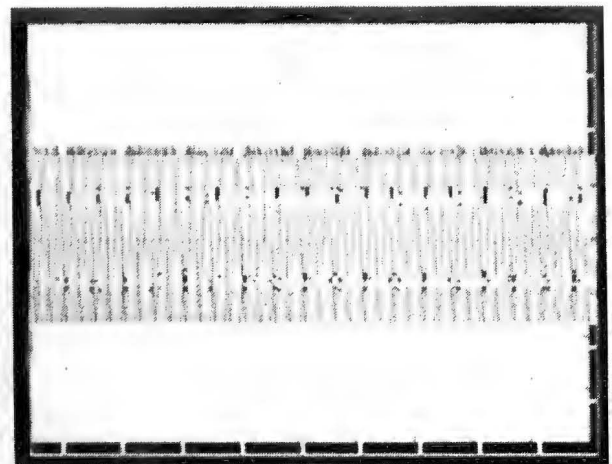


Figure 3.4: Rotor currents on full load
Balanced voltage

(b) Torque and Speed

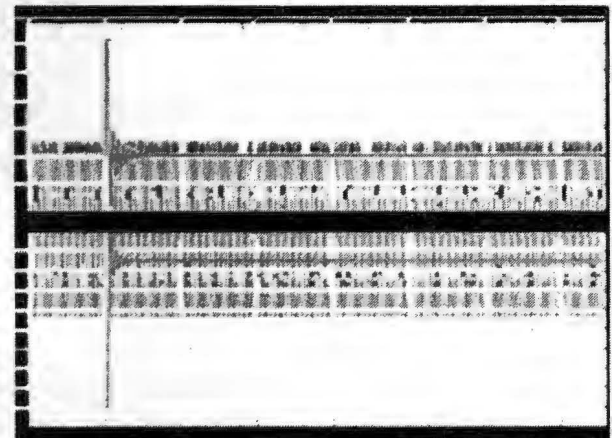


Figure 3.5: Electromagnetic torque and
Rotor speed on no load balanced voltage

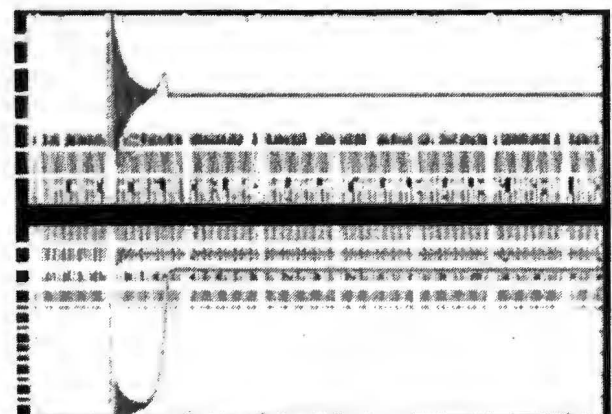


Figure 3.6: Electromagnetic torque and rotor
speed on full load balanced voltage

Simulating Three-Phase Induction Motor Performance under Unbalance Voltage Condition.

3.1.2 Voltage Unbalance – Under Voltage (a) Stator and Rotor Currents



Figure 3.7: Rotor currents on full load at under-voltage unbalance.

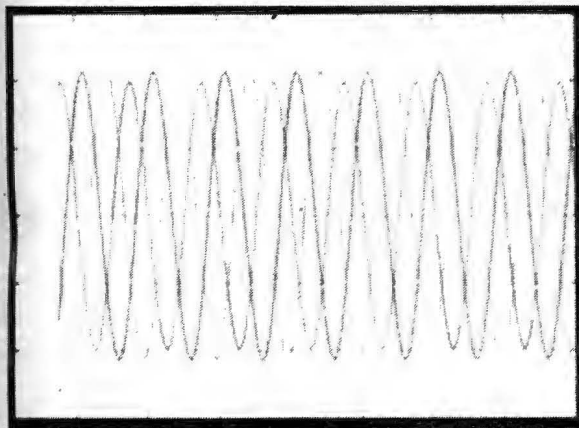


Figure 3.8: Stator currents at full load of under-voltage unbalance.

(b) Torque and Speed

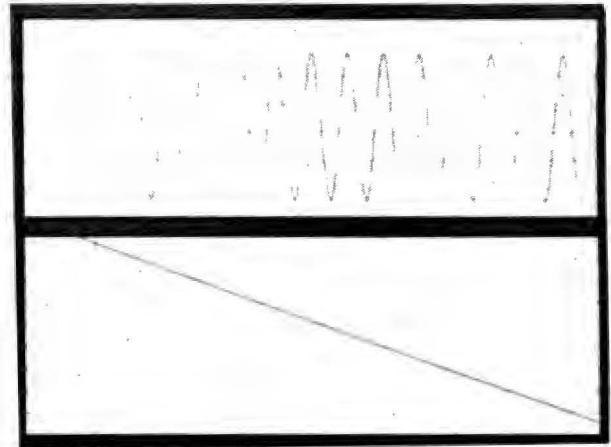


Figure 3.9: Electromagnetic torque and rotor speed at full load torque at under voltage unbalance (VUF of 2-10% with positive sequence voltage fixed at 0.95 of rated voltage).

3.1.3 Voltage Unbalance – Over Voltage (a) Stator and Rotor Currents

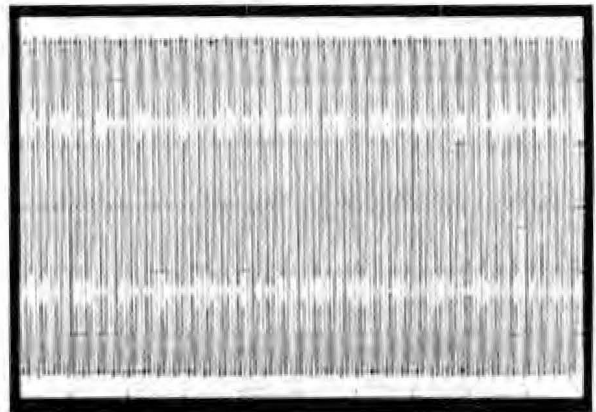


Figure 3.10: Rotor current at full load over-voltage unbalance.

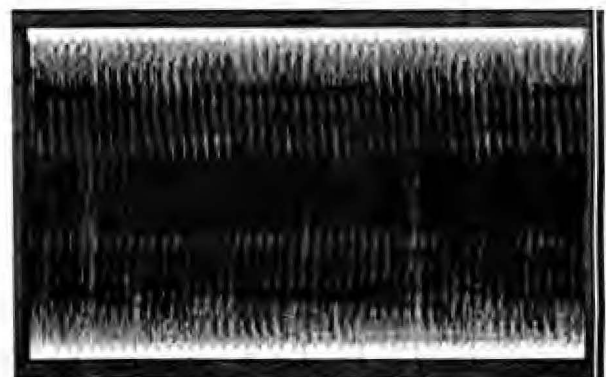


Figure 3.11: Stator current at full load over-voltage unbalance.

b) Torque and Speed

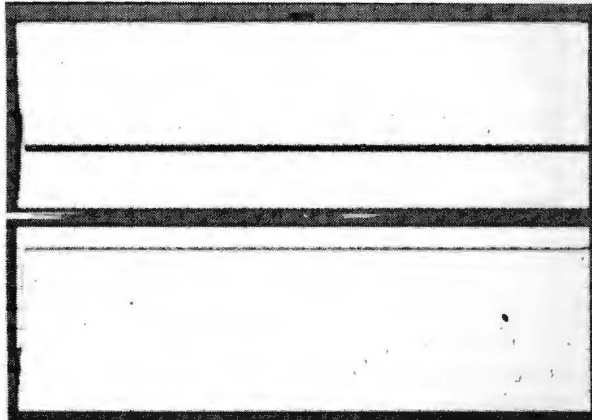


Figure 3.12: Electromagnetic torque and rotor speed at full load over voltage unbalance (VUF of 4% with positive sequence voltage fixed at 1.05 of rated voltage).

3.1.4 Voltage Unbalance – Rated Voltage

(a) Stator and Rotor Currents

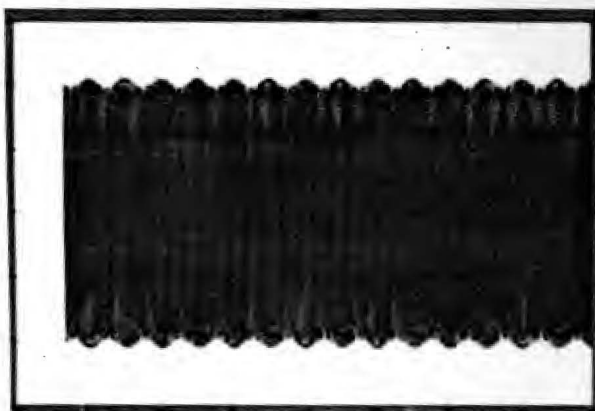


Figure 3.13: Rotor currents at full load rated voltage unbalance.

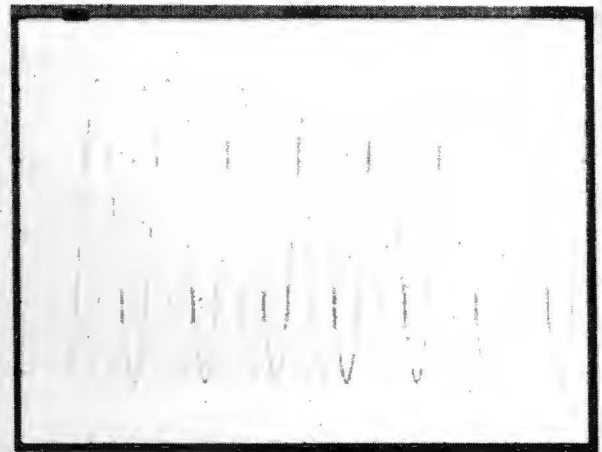


Figure 3.14: Stator currents at full load rated voltage unbalance.

(b) Torque and speed

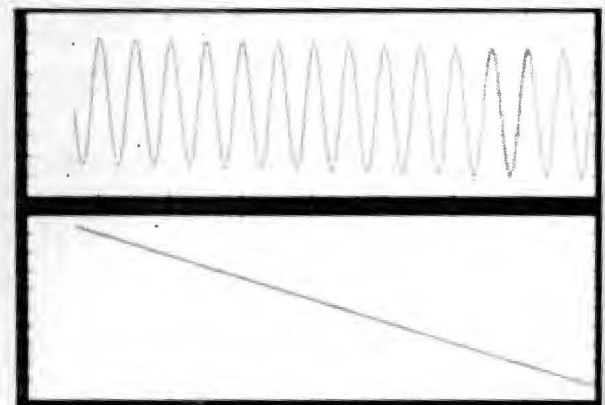


Figure 3.15: Electromagnetic torque and rotor speed at rated voltage unbalance at full load (VUF of 2-10% with positive sequence voltage fixed at the value of the rated voltage)

3.1.5 Measured Machine Laboratory Voltage

(a) Stator and Rotor Currents

Simulating Three-Phase Induction Motor Performance under Unbalance Voltage Condition.

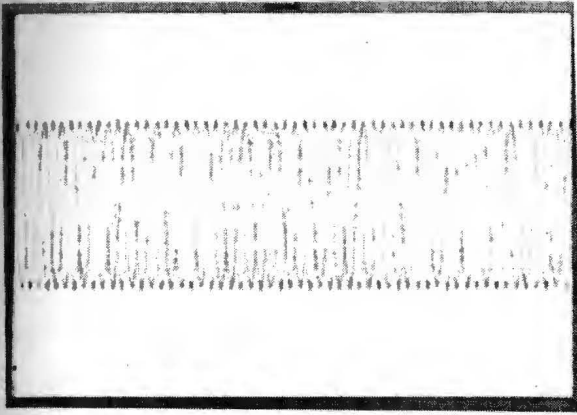


Figure 3.16: Induced rotor currents at measured machine laboratory voltage.

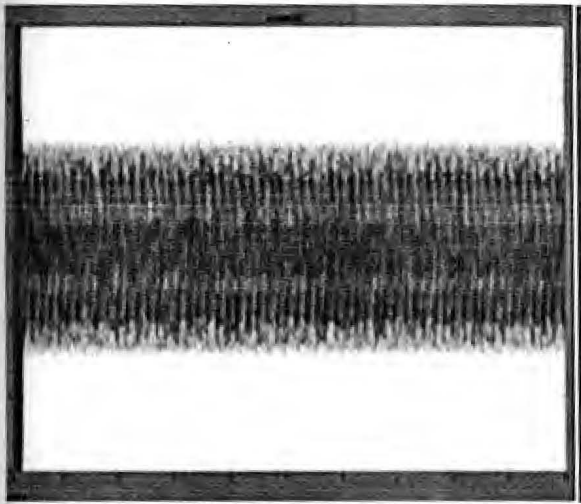


Figure 3.17: Stator currents at measured machine laboratory voltage.

3.2 Discussion of Results

3.2.1 Balanced Voltage

(a) Stator and rotor Currents

The three-phase stator currents were steady (Figures 3.1 and 3.2) and the induced rotor currents were uniform and linear as seen in (Figures 3.3 and 3.4). Induced rotor current on no load was 0.5A and 15A on full load while stator current was 3.5A and 17A on no load and full load respectively.

(b) Torque and Speed

The electromagnetic torque and rotor speed were smooth, stable and steady in less than 0.4s on no load and in 0.6s on full load (Figures 3.5 and 3.6).

(b) Torque and speed

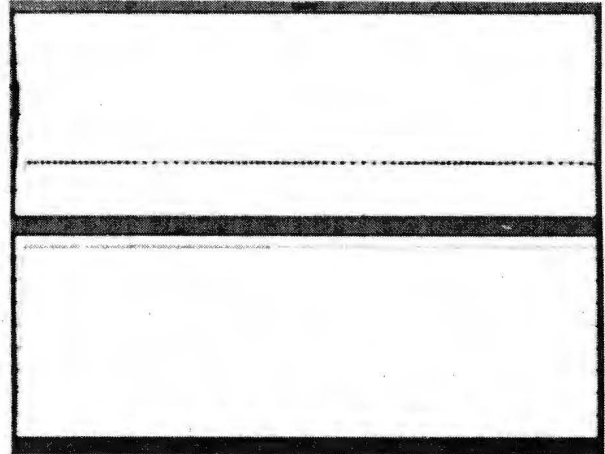


Figure 3.18: Electromagnetic torque and rotor speed on full load at measured machine laboratory voltage.

3.2.2 Voltage Unbalance – Under Voltage

(a) Stator and rotor Currents

The waveforms indicated rippled and cloudy stator and rotor currents on full load at under voltage unbalanced conditions (Figures 3.7 and 3.8). Rotor current were above indeterminate, 23A, 18A on full load, 75%, and 50% of load respectively. Stator currents were indeterminate, 25A, and 20A on full load, 75%, and 50% of load respectively.

(b) Torque and speed

At under voltage unbalance, for all values of VUF, the motor's torque and speed were undefined for full load operation (Figure 3.9). However, at reduced loads, the outputs were determinate with indications of growing gross ripples as the value of VUF increases.

3.2.3 Voltage Unbalance – Over Voltage

(a) Stator and Rotor Currents

The rotor currents were 25A, 18A and 12A on full load, 75% and 50% of full load respectively (Figure 3.10). Stator currents were 28A, 20A and 14A on full load 75% and 50% of full load respectively (Figure 3.11).

(b) Torque and Speed

The waveform indicated a lower level of undulation for both torque and speed when compared with under voltage unbalance of the same VUF. Like the under voltage unbalanced condition, the undulation increased with an increasing VUF with alarming ripples above VUF of 4%. (Figure 3.12)

3.2.4 Voltage Unbalance – Rated Voltage

(a) Stator and Rotor Currents

The waveforms indicated rippled and cloudy stator and rotor currents on full load at rated voltage unbalanced conditions (Figures 3.13 and 3.14). Rotor current were indeterminate, 20A, 13A on full load, 75%, and 50% of load respectively. Stator currents were indeterminate, 22A, and 15A on full load, 75%, and 50% of load respectively.

(b) Torque and Speed

At rated voltage unbalance, for all values of VUF, the motor's torque and speed were undefined for full load

Operation (Figure 3.15). However, at reduced load, the outputs were determinate with indications of ripples at all levels of unbalance. Like the under voltage and over voltage unbalanced condition, the undulation increased with an increasing VUF, but with alarming ripples above VUF of 4%.

3.2.5 Measured Machine Laboratory Voltage

The values of the measured voltages from the Department's machine laboratory presented in Table 2.3 gave a VUF of 1.4%.

(a) Stator and Rotor Currents

The waveforms indicated rippled and cloudy stator and rotor currents on full load at measured machine laboratory voltages. Rotor current was 6A while stator was 7A on full load (Figures 3.16 and 3.17).

(b) Torque and Speed

The electromagnetic torque produced was rippled showing inefficient operation, but not

with indication of gross inefficiency when compared with simulation results of balanced voltages (Figure 3.18). As load was reduced however, the output torque became smoother.

Conclusively, the presence of ripples in both stator and rotor currents' waveform in all cases of unbalance voltages when motor was on load indicated the presence of harmonics. The simulation results showed more current drawn by the stator and more induced in the rotor as the load increased in all cases of unbalance. This implies that increased copper losses accompany voltage unbalance, which may lead to increased heating, horsepower load and thus a reduced rated output power. If this condition is extended for the motor operation, it may accelerate insulation breakdown and reduce motor life span. It was also clear from the results that the presence of ripples on the waveform is an indication of distorted electromagnetic fields leading to rotor noise and vibration during the operation of the motor. For all types of unbalance, motor should never be operated on full load. It was observed that the adverse effect of unbalance is most severe at under voltage conditions; drastic load reduction did not produce good motor performance with a low VUF.

At over voltage unbalance however, motor indicated fair performance at VUF of 2-4% with a load reduction of 50%. At rated voltage unbalance with VUF of 2-4%, good performance was observed on load reduction of 50%. Above VUF of 4% for all types of unbalance, motor operation became grossly inefficient and load reduction did improve operational performance of the induction motor.

4. Conclusion

The investigation has shown that there is a noteworthy difference in the performance of a 2hp induction motor under unbalanced source voltages compared to balanced source voltages. The results proved that the operational performance of an induction motor

Simulating Three-Phase Induction Motor Performance under Unbalance Voltage Condition.

can be studied using simulated result from MATLAB® Simulink without going through the arduous analytical method. Since unbalanced conditions cannot be completely eradicated, it is therefore essential that motors be protected against all types of unbalances with NEMA, IEC and IEEE specifications and appropriately rerated for effective and efficient performance.

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